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Design for Wire and Arc Additive Layer Manufacture

J. Mehnen[1], J. Ding[1], H. Lockett[2], P. Kazanas[2]
[1]Manufacturing Department, Cranfield University, Cranfield, Bedfordshire MK43 0AL
United Kingdom
[2]Department of Aerospace Engineering, Cranfield University, Cranfield, Bedfordshire MK43 0AL
United Kingdom
{j.mehnen, jialuo.ding, h.lockett, p.kazanas@cranfield.ac.uk}

Abstract
Additive Layer Manufacture (ALM) is a technique whereby freeform structures are produced by building up material in layers. RUAM (Ready-to-Use Additive Layer Manufacturing) is an innovative concept for building large scale metal ready-to-use parts. The design for RUAM has several process steps: the geometric design of the parts taking the complex process behaviour of the arc welding process into account; FEM to predict temperature and stress distributions to minimise part distortions; and efficient robot tool path design. This paper covers these essential design steps from a technical as well as practical point of view.

Keywords:
Manufacturing, Rapid product development, Design for Manufacture

1 INTRODUCTION

New Additive Layer Manufacturing (ALM) technologies are currently subject of significant interest from industry. New wire and arc welding based technologies provide new routes to manufacture ready-to-use large metal parts. Producing large scale and high quality parts with very high deposition rates is the aim of the RUAM (Ready-to-Use Additive Manufacturing) machine currently being developed at Cranfield University.

Aerospace industry estimates requirements of about 20 million tonnes of billet material over the next 20 years. With machining rates of ca. 90% and ever increasing material costs especially in titanium [1], conventional manufacturing strategies need reconsideration. The RUAM concept aims at reducing production costs by providing a new, sustainable, cost and time efficient manufacturing process which utilises well established as well as advanced cutting-edge technology.

RUAM workpieces are produced by building up of material in layers (see Figure 1). New technologies such as CMT (Cold Metal Transfer) or Interpulse Welding allow for high deposition rates being more than 10 times faster than conventional powder based technologies.

Figure 1: Layer structure of a wire based Additive Layer Manufacturing part

RUAM aims at integrating additive layer manufacturing and machining into one single machine. Figure 2 shows the general layout of the RUAM process structure.

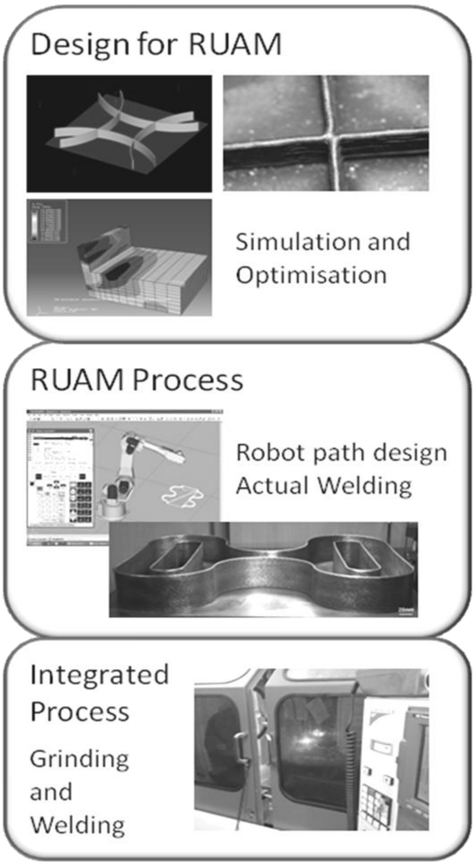


Figure 2: RUAM process structure

In order to achieve a well integrated process that utilises the full power of the additive layer manufacture technique, each process step has to be set up and linked optimally.

Design for RUAM identifies workpiece geometries that are most suitable for the final real-world applications. For example, in aerospace new light weight stiffeners are used which need to satisfy specific mechanical constraints. ALM is an ideal way of manufacturing and testing innovative designs because ALM lowers the constraints that one typically encounters in conventional manufacturing [2, 13, 14]. The precision of the arc welding process employed in the RUAM process depends on the welding strategy. Where necessary, the rough surfaces will be ground off by the integrated RUAM machine producing high precision industrial parts. The workpieces are fully dense.

Another step in the Design for RUAM is the analysis of the temperature and stress properties of the welded workpieces. In RUAM advanced fast FEM modelling techniques are used. FEM analyses help minimising workpiece distortions by identifying the most appropriate welding tool paths.

Design for RUAM also tackles the issues of how to choose the actual welding tool paths that are technically most suitable for the arc welding process.

In the actual RUAM Process, the actual welding paths are executed by a robotic system. A robot arm guides the welding torch along a prescribed tool path. In the RUAM process, the actual robot tool paths are directly calculated from the CAD geometry. The time consuming and tedious task of teaching the robot can significantly be reduced by new RUAM tool path calculation software. Typical robot training sessions using a pendant can take hours. Now, ready-to-use tool paths are provided within a couple of minutes. The best welding parameters are applied in the actual welding process. These parameters are determined by extensive welding experiments which have been performed in steel, aluminium and titanium. These parameters determine e.g. the optimal torch travelling speed or the best wire feed speed [3].

Figure 3: 1000mm x 200mm x 4 mm RUAM titanium wall structure

The aim of the RUAM project is to generate large and precise metal parts rapidly using an integrated process. With RUAM up to 15m workpieces could be manufactured by using high welding deposition rates while the precision is provided by e.g. additional grinding steps. Precision and manufacturing time is improved by keeping the workpiece within one single machine during the whole RUAM process. The additive layer manufacturing technique has the additional advantage that, due to the sequential manufacturing technique, now sections of the workpiece can be accessed that are generally inaccessible.

The first large ALM parts have been produced successfully (Figure 3). The travel speed was 4.5mm/sec. The time to produce this 1m titanium part was 12.3 hours. Manufacturing large components such as this wall using selective laser sintering (SLS) would be very uncommon due to the size limitations of conventional SLS machines.

Currently, the RUAM process focuses mainly on applications in aerospace industry. However, repair and cladding applications are also foci of ongoing RUAM research activities.

This paper touches on the Design for RUAM and the RUAM process itself. In particular, the design of unconventional stiffeners and their ALM manufacturing as well as FEM modelling aspects of additive layer manufacture and the automatic design of robot tool paths from CAD data will be discussed.

2 DESIGN FOR RUAM

2.1 ALM Design Study

ALM has the advantage that one can manufacture parts with high levels of geometry complexity. However, also ALM has its limitations which have to be taken into account during the design for ALM. For example the achievable maximum wall thickness, material properties and some design features (e.g. maximum inclination of walls) might have an impact on the desired design.

An initial RUAM design study has investigated various designs for stiffened panes. These light weight panes can be used for aerospace applications. The ALM process allows the design of even quite unconventional structures that show a maximum buckling index. The buckling index is the buckling load per kilogram. The higher this index the better the stiffened structure. ALM parts can be designed to specific load cases and can therefore be more flexibly designed than workpieces that are fabricated e.g. from sheet metal. More recently stiffened panels have been machined from single block material. ALM provides a more sustainable solution because no material is wasted by this process.

The Design for RUAM for stiffened panels has been done first *in silico*. A CAD model of the stiffener was generated and FEM stress analyses performed. Five different panel designs for uni-axial loads were followed by four designs for bi-axial loads. Figure 4 shows some selected panel designs for uni-axial loads.

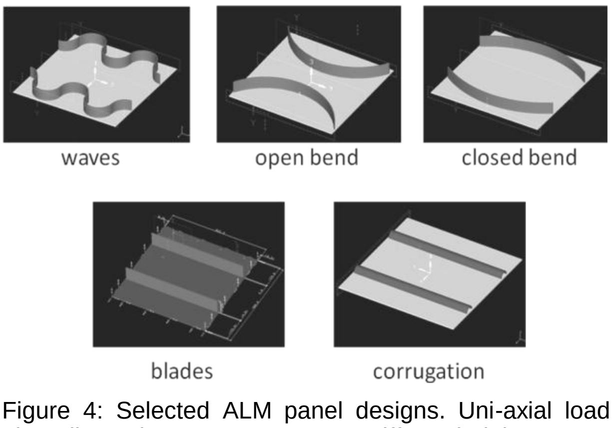


Figure 4: Selected ALM panel designs. Uni-axial load, plate dimensions: 500 x 500 mm, stiffener height: 50 mm, materials: Ti 64, generic mild steel.

The results of the analyses are shown in Figure 5. The bucking index in kN/kg has been introduced to account for the mass of a structure. A lighter structure with the same buckling load will get a higher score.

One can see that the simple unsupported plate has, of course, a very small buckling index of 3.61 and 3.71 for titanium and steel, respectively. The complex wave structure has only a slightly higher index than the plain steel plate. Thus, this design can be ruled out as a useful support solution. The corrugation design has a nearly 14 times higher buckling index than the plain plate. It is also important to notice that the corrugation is stronger in titanium than in mild steel. In our experiments this property is predominant for this type of geometry.

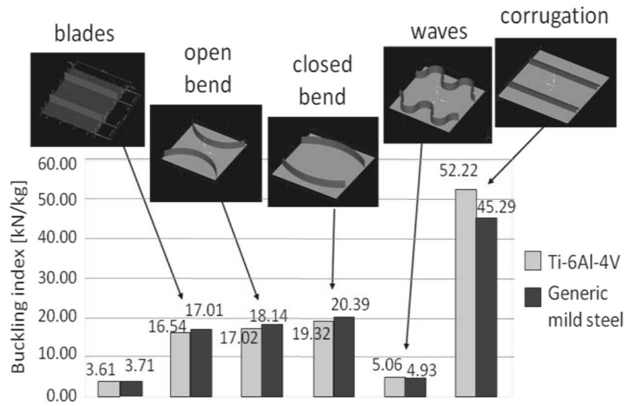


Figure 5: Selected ALM panel designs with uni-axial load applied.

Analysis of curvilinear stiffeners (not shown) showed some space for improvement for bi-axial loading as well. Here manufacturing cross structures becomes important.

An example of a manufactured stiffened panel produced by the RUAM process can be seen in Figure 6.

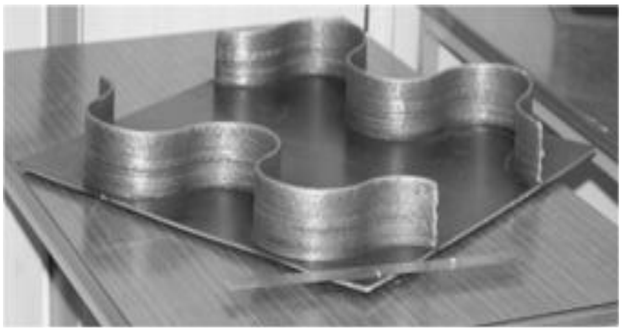


Figure 6: Stiffened plate with wave structure using 1.0 mm wire, wire feed speed 3.3m/min, deposition rate 1.22kg/h, manufacturing time 2.56h.

2.2 Welding Strategies for Cross Structures in Steel

An initial investigation into the feasibility of manufacturing stiffened panel structures using wire additive layer manufacture has been performed. To date the study has focussed on the manufacture of wall crossings as shown in Figure 7. The process utilised was the Cold Metal Transfer (CMT) which could be classified as a Gas Metal Arc Welding (GMAW) variation. The welding parameters were set to produce 4 mm wall with 0.8 mm steel wire. The torch movement is robot controlled.

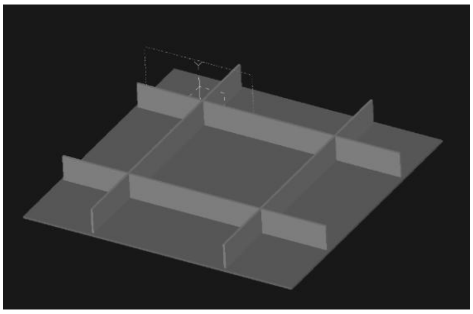


Figure 7: Example of a stiffened panel with crossings.

The difficulties of producing wall crossing using wire based ALM are associated with the build up of peaks where the weld beads overlap at the crossing points.

A number of different build strategies have been investigated including changes to the travel speed direction and build pattern. These build strategies have a significant impact on the effective wall thickness, surface roughness and repeatability of the final result. The reduction or elimination of undesirable features such as stress raising sharp corners and peak development (see Figure 8) and crossover failure in the intersection was also studied.

Figure 8: Example of peak development.

The experiments have demonstrated that it is possible to achieve good quality results using a pattern of opposite angles connecting at their vertices and a direct crossing pattern. The pattern of opposite angles gives the best results and produces smooth radii in the corners (see Figures 9 and 10), but it is more complex to program. The direct crossing pattern is easier to program, but can cause sharp angles in the corners, which could act as stress raisers. Crossing features have been successfully produced with heights of up to height 100 mm and wall thicknesses of 4 mm.

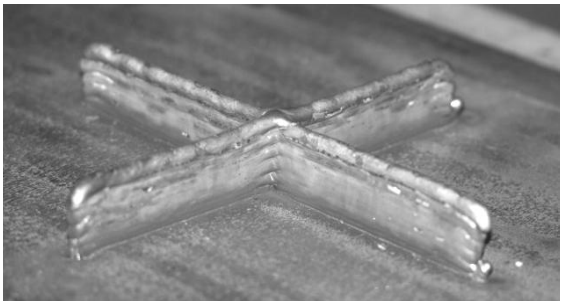


Figure 9: Example of crossing feature manufactured using pattern of opposite angles.

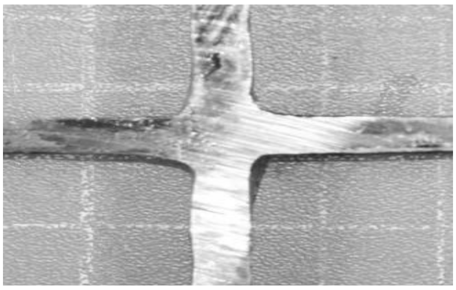


Figure 10: Example section through crossing feature showing radii in corners.

Future work will concentrate on the development of build strategies for inclined walls, wall crossings with curvilinear stiffeners and wall crossings with angles other than 90°.

2.3 FEM Modelling of ALM Processes

The wire based welding techniques used in the RUAM project, such as GTAW and GMAW, can provide high deposition rates. However, the large heat input of these processes also brings big residual stress and distortion. These issues can badly impact the accuracy of the final shape of the parts and their mechanical properties. Therefore, it is highly important to study the thermo-mechanical behaviour of the ALM process.

FEM simulation of welding processes started from 1970s. It is widely utilised and provides accurate results for many different arc welding processes [4, 5, 6]. In contrast to these welding processes, the material in the ALM process is reheated several times. The mechanical properties cause by the reheating effect between adjacent droplets has been analysed by [7, 8].

In order to find out the optimal build patterns for building parts with minimum residual stress and distortion, studies on the thermo-mechanical performance of the ALM process has been carried out in RUAM project. The commercial FEM software ABAQUS® is employed for this task.

Tree dimensional FEM models are built for the straight wall shaped ALM parts. To save computational time, only half of the parts are modelled with symmetric constrain conditions. Sequentially coupled thermo-mechanical simulation is performed in which the transient temperature distribution is applied as input for the mechanical simulation. Temperature depended material properties are used for both thermal and mechanical simulation.

The heat source is modelled using the Goldak ellipsoidal model moving along the weld bead [9]. The material adding process is modelled by activating the meshes successively with the moving heat source. The model is meshed with biased linear elements which become coarser the further they are away from the weld bead. The thermal boundary conditions include convection heat loss and radiation heat loss.

Figure 11 shows the temperature distribution of a wall with five layers. From this figure one can see that the previous layers are reheated when new layers are added. Figure 12 shows an example of a detailed temperature history plot of the node located on the weld central line of the middle section along the weld direction (Node 1 in Figure 11). When the heat source passes node 1 in the first layer the material is heated up to ca. 1,800° C (max. temperature). With each further layer deposited the maximum temperature at node 1 decreases exponentially. A delay of 10 minutes between each pass was used to allow for the material to cool down to room temperature.

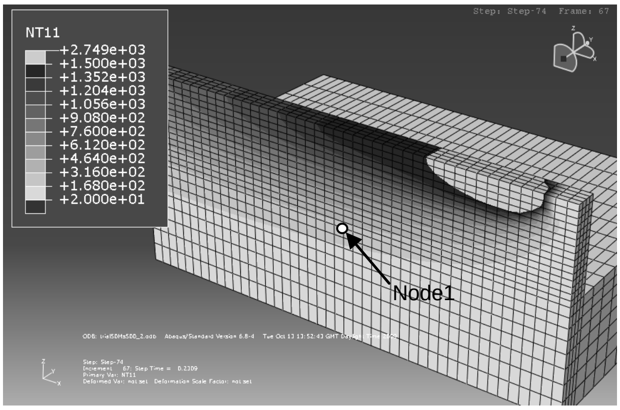


Figure 11: Temperature simulation of the AML process.

The mechanical model uses the same meshes as the thermal model but changes the element type for the stress analysis. The load imposed on the model comes from the nodal transient temperature results from the thermal simulation. Boundary constrains are added to the edge of the plate for simulating clamping conditions. Apart from using temperature dependent mechanical material properties, the plastic strain annealing phenomenon is also considered in the simulation.

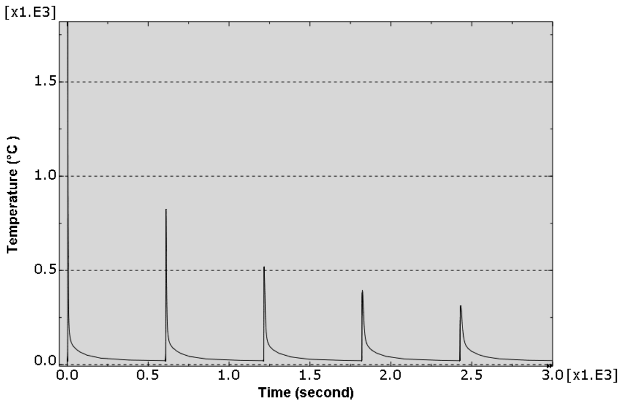


Figure 12: An example of nodal temperature history.

The contour plot presented in Figure 13 shows the final longitudinal stress distribution which is the main source of the distortion of the straight wall part. Notable tensile stress is located on the layered wall (ca. 550 MPa) and the compress stress is mainly distributed in the base plate near the weld bead (ca. -200 MPa).

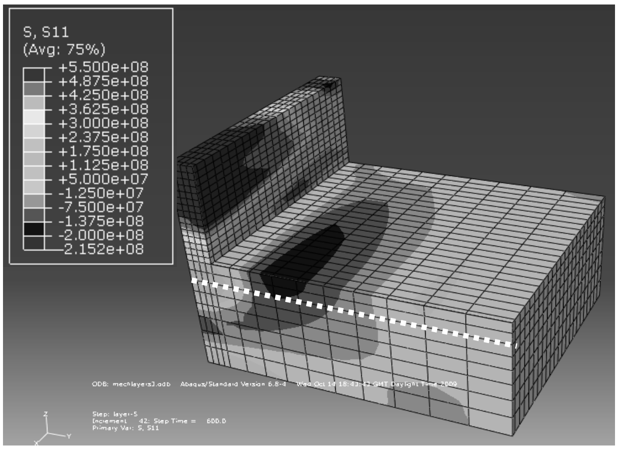


Figure 13: Final longitudinal stress distribution. The dotted line indicates the points of temperature measures displayed in Figure 14.

Figure 14 shows the longitudinal stress values of points 2 mm below the top surface of the base plate and in the middle section of the part (see dotted line in Figure 13). The different curves show the stress distribution after the deposition of each layer. From this figure one can see that the reheating effect causes a significant stress reduction whenever new layers are deposited on previous layers.

In the future the FEM model aims to reduce distortions of ALM parts by providing accurate predictions that can be used to design different welding strategies.

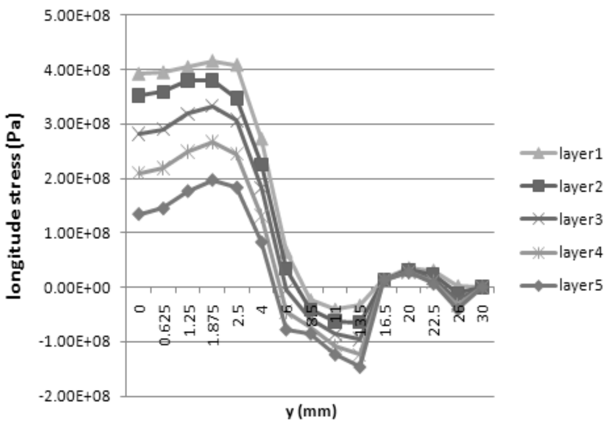


Figure 14: Longitudinal stress plot on the symmetry plane 2 mm below the top surface of the base plate.

2.4 Robot path determination

In the RUAM project, a 6-axis Fanuc Robot is adopted for holding the welding torch making the ALM process very flexible. One advantage of the robot system is that it can deal with rather large parts. However, conventional robot programming with a teach pendant is generally very time-consuming especially for complex paths. Therefore, an automatic robot path generation tool is required to generate robot code directly from CAD models.

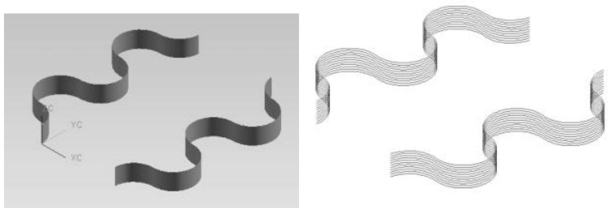
"Mirroring" milling tool paths generated from commercial CAD/CAM software or using slicing routines from Rapid Prototyping software are two ways of getting tool paths [10]. However, both these ways are not flexible because of software constrains. Therefore, researchers often develop their own tools to achieve specific part designs. Ribeiro developed a robot off-line programming system based on AutoCAD. This system can slice CAD models and generate robot programmes for ABB robots automatically [11]. Zhang developed a path planning and generation system based on the IGES format CAD models [12].

For the RUAM project, a robot path generation program RUAMROB© has been developed in Matlab 7.1. This tool contains two main modules – a slicing module and a robot program generation module. By executing these two modules automatically, the program can slice the designed ALM parts and generate the ready-to-use path code for a Fanuc robot in one go. A user-friendly interface for RUAMROB© has also been developed to simplify the setting of parameters.

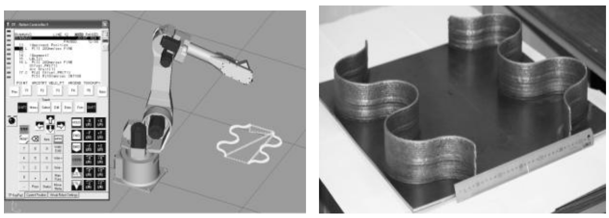
The function of the slicing module generates isolines from the CAD model and produces the sequenced points on the path. The algorithm generated for this module can remove duplicate points which usually appear when CAD models with poor triangulation quality are sliced. The program also supports the user in reducing the number of output points by setting up the tolerance which is very useful for building large parts.

The robot program generation module takes these points and generates a Fanuc robot program in ASCII format. Some key parameters for the welding process can easily be set by the users, including welding process parameters such as arc on/off position, travel speed of the welding torch, waiting time between layers, building sequence for the part with several sub-parts, etc. The output robot program can be simulated and checked using the Fanuc robot off-line software ROBOGUIDE©. The software also translates the program from ASCII format into binary format that can be executed by the robot.

Figure 15 shows the general process of building an ALM part from a CAD model. The RUAMROB© program first slices the CAD model (Figure 6(a)) from STL data [15] into isoline paths (Figure 6(b)), and then generates the robot program which can be checked in the simulation (Figure 6(c)). Figure 6(d) shows the manufactured ALM part using the generated robot program. The total time spent on the robot program generation with RUAMROB is just several minutes. Comparing to the previous experience of using a teach pedant, a huge amount of robot programming time can be saved. Moreover, it also makes building complex three dimensional ALM parts possible.



(a) (b)



(c) (d)

Figure 15: Robot path generation process.

3 SUMMARY

The RUAM process is an innovative concept that opens a vast space of options for manufacturing efficiently complex geometries. The RUAM process is especially useful e.g. in manufacturing or repairing parts for aerospace industry. Due to the high flexibility of the ALM process, these parts can be tailor made. The arc welding process provides very favourable material properties yielding ready-to-use parts.

The process chain consists of several steps that are feeding into each other. In the Design for RUAM step, new geometries are generated which have systematically been tested and optimised. This part of the RUAM project will provide a handbook for ALM incorporating design rules and features.

In order to produce high quality parts extensive experiments and simulations are needed. FEM temperature and stress analyses help understanding and improving the ALM welding process. The FEM analyses can help in minimising distortions and identifying best welding strategies. The results have been verified with examples from literature and real-world tests.

The gap from CAD design to robotic manufacture of ALM parts has been closed by an automatic path generation tool. The tool generates FANUC robot paths directly from CAD geometries. The tools paths do not integrate expert knowledge yet. Currently, directions as well as speed etc. are decided manually following the recommendations form the design handbook, FEM analyses and welding experiments.

Future work focuses on rescaling the RUAM machine and improving the integration of each process step into one single automated smooth process. Sustainability analyses on various industry case studies are part of ongoing research.

4 ACKNOWLEDGMENTS

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